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# Registration of technical drawings and calibrated images for industrial augmented reality

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**Abstract.** Despite tremendous progress in 3D modelling technology, most sites in traditional industries do not have a computer model of their facilities at their disposal. In these industries, 2D technical drawings are typically the most commonly used documents. In many cases, a database of fully calibrated and oriented photogrammetric images of parts of the plant is also available. These images are often used for metric measurement and 3D as-built modelling. For planning revamps and maintenance, it is necessary to use industrial drawings as well as images and 3D models represented in a common "world" coordinate system. This paper proposes a method for full integration of technical drawings, calibrated images and as-built 3D models. A new algorithm is developed in order to use only a few correspondences between points on a technical drawing and multiple images to estimate a metric planar transformation between the drawing and the world coordinate system. The paper describes the mathematical relationship between this transformation and the set of homographies needed for merging the technical drawing with all the calibrated images. The method is implemented and fully integrated into an industrial software we developed for 3D as-built reconstruction. We present examples of a real application, in which the method is successfully applied to create an augmented reality representation of a waste water plant.

**Key words:** Industrial augmented reality – As-built reconstruction – Technical drawings – Planar motion estimation – Camera calibration – Combining orthographic and perspective views

## 1 Introduction

Three-dimensional modelling technology has made enormous progress in recent years. In all kinds of manufacturing industry, CAD models have become essential for the entire production process. However, in many parts of traditional industries, such as the chemical or power generation industries, many manufacturers do not have 3D models of their facilities and production lines. Since these plants are often several decades old, the only existing documents are technical drawings such as floor maps, pipe layouts, and wiring plans. Many of these drawings are not even updated in detail. For maintenance purposes or revamps, it is essential to generate and use precise measurements or 3D models of current installations. For example, re-installations or changes to large components require a careful study of the environment to check whether the new part can be transported to where it has to be fitted. Photogrammetric methods are often used to obtain the measurements necessary, the first step always consisting of camera calibration. In general, these methods rely on point correspondences over a series of photogrammetric images, and different marker-based and marker-less methods are used to obtain these correspondences. Based on these calibrated images, 3D measurements can be made or, if necessary, an as-built 3D model can be created (see Fig. 1). Section 2 gives a brief overview of this process.

In many cases the 3D models, which only contain geometric information, are not enough for planning purposes. Technical drawings (see Fig. 2b) often include additional information that needs to be taken into account during the planning process. Currently, it is the task of highly trained specialist engineers to combine as-built reconstruction data and technical drawings. This is one of the bottlenecks in the whole planning workflow, as it is time consuming and often erroneous. In addition, details in technical drawings may be outdated, and the experts need to carefully compare the as-built model with the drawings before combining them. The superimposition of photogrammetric images and technical drawings would significantly improve the planning process in terms of speed and accuracy. Blending the drawing into the image provides information at the right point, and leaves no room for misinterpretation of the drawing. Such a system was first introduced by Navab et al. [4] based on direct homography between the drawing and the image. Figure 3 gives an example of such an overlay. Simultaneous superimposition of images, drawings and 3D models creates a new and rich set of documents (see Fig. 4). In some factories the floor maps are only available as scanned blueprints, whereas

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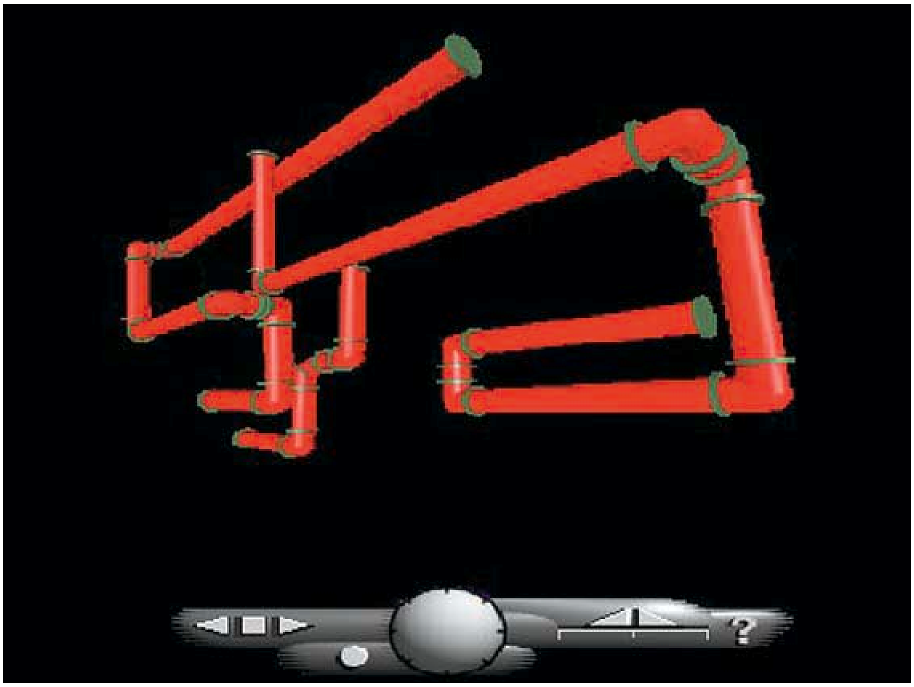
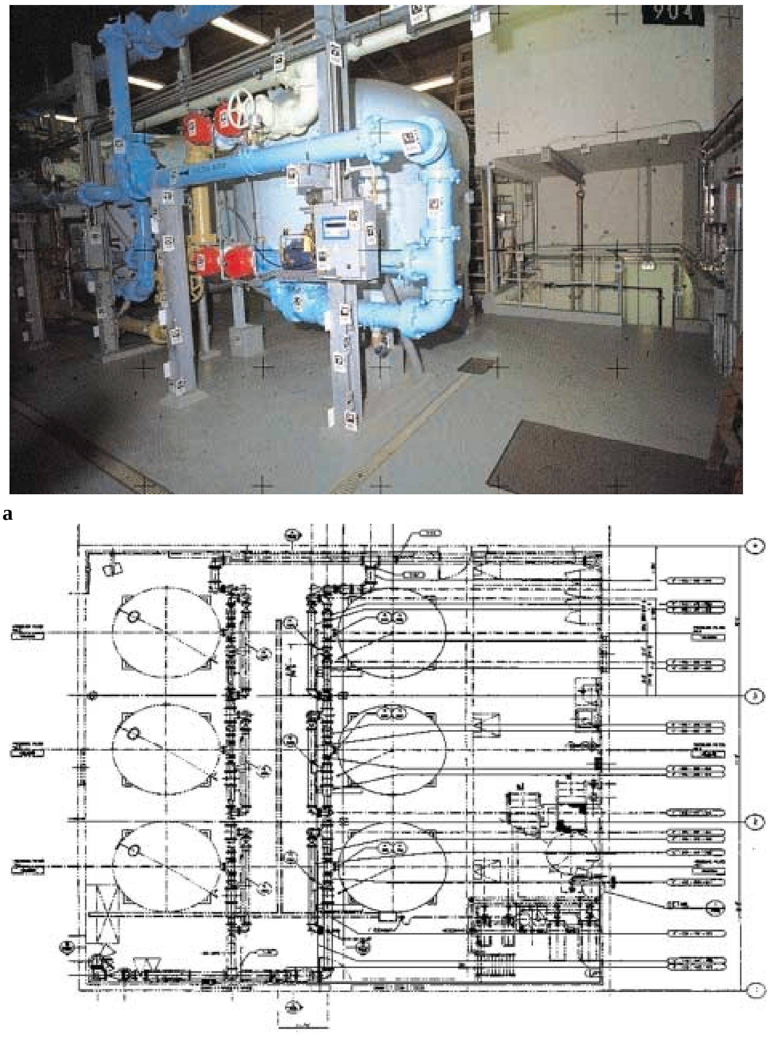


**Fig. 1.** 3D reconstruction of a piping installation




a

b

**Fig. 2.** A photogrammetic image from a waste water plant (**a**) and the associated floor map of the facility (**b**)

**Fig. 3.** Visual combination of a photogrammetric image and a technical drawing

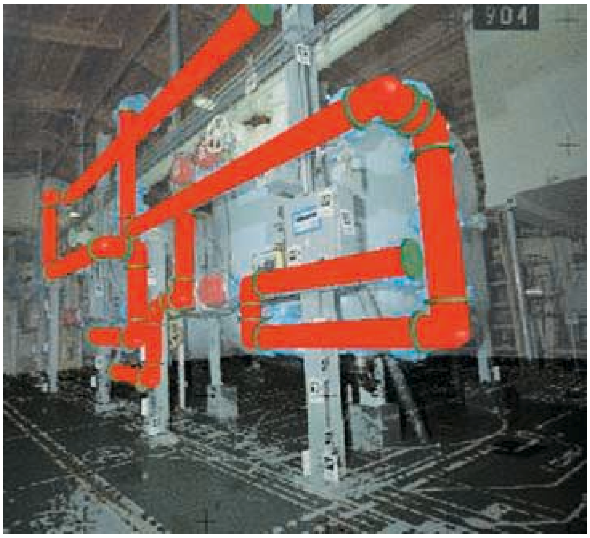


**Fig. 4.** Augmentation of a photogrammetric image of a waste water plant by the associated floor map and 3D reconstruction of pipework

in others they may be available in a vectorized format containing hyperlinks to databases. In the latter case, additional documentation such as maintenance plans, CAD models or to-do lists can be accessed by clicking on the object of interest in the overlayed image. We call such a database of augmented images a *transparent factory*.

In this paper, we propose a mathematical framework to integrate an industrial drawing into a set of calibrated images by computing a unique planar transformation **M**. This transformation is computed from a set of sparse point correspondences between images and drawings. Here, we take the example of a top view drawing, often called a floor map. The point correspondences are established interactively, with a minimum number of correspondences resulting in an initial estimation of matrix **M**. The floor map can then be superimposed onto any of the database images. To increase accuracy, the user can identify more correspondences on the overlaid images. Due to superimposition, the selection of additional correspondences between floor map and images becomes a quick and easy process. Each additional pair of correspondences increases the accuracy of superimposition on all of the images.

In the rest of the paper, we first describe the usual method for creating calibrated image databases. We then introduce our mathematical framework for the integration of industrial drawings into this database. The method is implemented and fully integrated into industrial software that we developed for 3D as-built reconstruction. The necessary conditions and minimum number of correspondences are then described. Two series of experiments are conducted, and the results are presented in Sect. 6. In particular, we present examples of a real application in which the method is successfully applied to create an augmented reality representation of a waste water plant.

## 2 Database of calibrated images

This section briefly describes the usual procedure for creating databases of calibrated images in industrial applications. Here, by *calibrated* images we mean that both intrinsic and extrinsic camera parameters are known, that is, all parameters of the camera model (i.e. position, orientation, principal point, focal length, skew and radial distortion) need to be known or estimated. Frequently, an initial estimate for the intrinsic parameters of the camera is given by the provider. If this is not the case, the internal camera parameters can be estimated in an offline process, usually done by viewing a calibration grid with known geometry [9]. As the final step of the calibration procedure, the initial estimate is fed into a bundle adjustment program, which optimizes both the intrinsic and extrinsic parameters of all cameras by minimizing the back-projection errors.

The database of calibrated images is created once, and only needs to be updated every few years. Professional (digital) cameras with a fixed focal length are often used for this purpose. These cameras also provide accurate information on the radial distortion. In general, photogrammetric cameras are physically stable, so only one set of intrinsic camera parameters is used for a complete series of images.

Many camera calibration algorithms have been proposed in the literature [11, 3, 7, 1, 8, 12, 13]. Recently, Navab et al. [5] proposed the use of images and industrial drawings for a combined calibration of perspective and orthographic cameras. Many of the existing calibration algorithms require a large number of point correspondences between the images. One needs to detect these feature points and establish the correspondences. Accurate detection of corners and T-junctions has been the subject of research for many years [2, 6]. These methods provide a set of primitives, which often includes spurious points, and misses many of the useful point features. In industrial environments a large proportion of the images often include cylindrical objects that provide occluding edges. Therefore, most of the corners and T-junction points are also created by the intersection of these occluding edges, making the correspondences difficult to establish, and thus sometimes inaccurate.

The most practical solutions for automatic point detection and correspondences introduce coded markers into the scene. The markers are printed and attached at arbitrary positions onto walls, piping, etc. (see Fig. 5). Intelligent image processing software can automatically detect and recognize 2000 different such markers. This solves both the detection and correspondence problems. The next step is the estimation of camera parameters.

A small number of markers, between three and ten, are measured manually, and fix both our metric and our world coordinate systems. A combination of pose estimation and structure from motion algorithms, followed by bundle adjustment, uses these data – as well as point correspondences – to estimate all of the camera parameters. The bundle adjustment procedure uses a robust estimation algorithm to minimize the overall reconstruction/back-projection error. Once the camera parameters have been estimated, the images and their associated calibration data are entered into a database, and following the structure of the factory, are grouped into sections, rooms and floors.

The main objective of this paper is to propose a new method for registration of the industrial drawings and floor plans with the image database and its associated world coordinate system. This increases the value of such an image database considerably. This new method may result in many applications for computer vision algorithms – including image-based retrieval and automatic hyperlinking – within existing industrial workflow.

## 3 Notation

In this paper, we denote a 3D point as $\mathbf{x} = (x, y, z)^{\mathrm{T}}$ in the world (factory) coordinate system, as $\mathbf{x}_i = (x_i, y_i, z_i)^{\mathrm{T}}$ in each camera coordinate system, and as $\mathbf{x}_F = (x_F, y_F, z_F)^{\mathrm{T}}$ in the floor map's coordinate system. We have a database of $n$ fully calibrated photogrammetric images (see Sect. 2 for details). This means that we have both intrinsic parameters $\mathbf{A}_i$ and extrinsic parameters $\mathbf{R}_i, \mathbf{t}_i$ for all of the cameras. Transformation of a 3D point from the world coordinate system to each camera coordinate system yields

$$\begin{pmatrix} x_i \\ y_i \\ z_i \\ 1 \end{pmatrix} = \begin{bmatrix} \mathbf{R}_i & \mathbf{t}_i \\ \mathbf{0} & 1 \end{bmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} . \tag{1}$$

Projection of a 3D point onto a camera yields

$$\begin{pmatrix} \lambda u_i \\ \lambda v_i \\ \lambda \\ 1 \end{pmatrix} = \begin{bmatrix} \mathbf{A}_i\mathbf{R}_i & \mathbf{A}_i\mathbf{t}_i \\ \mathbf{0} & 1 \end{bmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} , \tag{2}$$

where $\mathbf{A}_i$ represents the intrinsic parameters of camera $i$ [1]:

$$\mathbf{A}_i = \begin{pmatrix} \alpha_i & 0 & \gamma_i \\ 0 & \beta_i & \delta_i \\ 0 & 0 & 1 \end{pmatrix} . \tag{3}$$

In this paper, the floor map is modelled as an image taken by an orthographic camera. The transformation between the floor map and world coordinate system is then described by $(\mathbf{R}_F, \mathbf{t}_F)$.

## 4 Alternative methods for images/drawing registration

In this paper, the transformation between the drawing and world coordinate system is estimated using sparse correspondences between the images and drawings. This is then used to recover a set of homogeneous planar transformations called *homographies*, blending the drawing into all of the images. This section describes some existing alternative methods.

### *4.1 Direct homography between drawing and image*

The homography between the drawing and each image could be estimated separately using a set of at least four point and/or line correspondences [4]. The correspondences should be made for features that exist on the actual plane in the factory. However, it is difficult and cumbersome to establish such a large number of correspondences for each image separately. In addition, features in technical drawings are not always visible in the images. For example, if only pipes and not their vertical support structures are visible, there would be no feature point correspondence between the drawing and the floor of the factory in the image (see Fig. 5).

Even if there are correspondences on the actual floor plane, they are often occluded by additional installations such as pipelines or steel construction. In fact, in most cases one cannot find a sufficient number of correspondences (at least four) between a single image and a technical drawing in order to directly compute the homography. The method proposed in this paper does not require point correspondences to all images. It needs a minimum of only five point correspondences to at least two images. There are no further constraints on the existence or number of correspondences to each image in the database.

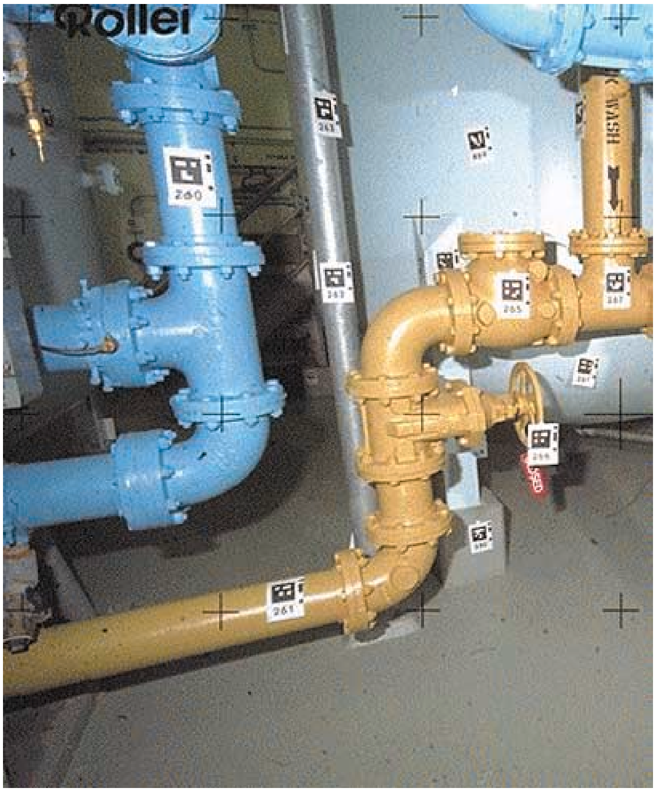


**Fig. 5.** In many images correspondences to the ground plane cannot be found

### 4.2 Stereo reconstruction and 3D/2D matching

Another option which seems easily implementable is the 3D reconstruction of points on the floor using multiple images. The correspondence between reconstructed points and 2D points on the drawing needs to be established. These 3D/2D correspondences can be used for orienting the technical drawing. However, this is not always possible, as many points are only visible on a single image. In addition, it is Labor-intensive to browse through an image database to establish stereo correspondences. The method proposed in this paper does not require correspondences between images, making the entire process practical and user-friendly.

## 5 A new method for image/drawing registration

We define the coordinate system associated with the technical drawing so that a point on the drawing is represented by $(x_F, y_F, z = 0)^{\mathrm{T}}$. The $4\times 4$ matrix $\mathbf{M}_{4\times 4}$ represents the transformation between the drawing's and the world coordinate system. We write:

$$\begin{bmatrix} \mathbf{A}_i\mathbf{R}_i & \mathbf{A}_i\mathbf{t}_i \\ \mathbf{0} & 1 \end{bmatrix} \mathbf{M}_{4\times 4} \begin{pmatrix} x_F \\ y_F \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \lambda u_i \\ \lambda v_i \\ \lambda \\ 1 \end{pmatrix}. \tag{4}$$

Note that $\mathbf{M}_{4\times 4}$ contains both intrinsic (i.e. scale and aspect ratio) and extrinsic (i.e. position and orientation) parameters of the technical drawing. To estimate the transformation $\mathbf{M}_{4\times 4}$, we rewrite (4) such that

$$\mathbf{M}_{4\times 4} \begin{pmatrix} x_F \\ y_F \\ 0 \\ 1 \end{pmatrix} = \begin{bmatrix} \mathbf{R}_i^{\mathrm{T}}\mathbf{A}_i^{-1} & -\mathbf{R}_i^{\mathrm{T}}\mathbf{t}_i \\ \mathbf{0} & 1 \end{bmatrix} \begin{pmatrix} \lambda u_i \\ \lambda v_i \\ \lambda \\ 1 \end{pmatrix}. \tag{5}$$

Since the technical drawing lies on the plane $z = 0$, the third column of $\mathbf{M}_{4\times 4}$ does not affect this transformation. Without loss of generality, we take:

$$\mathbf{M}_{4\times 4} = \begin{pmatrix} M_{11} & M_{12} & 0 & M_{13} \\ M_{21} & M_{22} & 0 & M_{23} \\ M_{31} & M_{32} & 0 & M_{33} \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{6}$$

Therefore, the metric planar transformation between the technical drawing and the world coordinate system is defined as:

$$\mathbf{M}_{3\times 3} = \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{pmatrix}. \tag{7}$$

In the following, we shall refer to $\mathbf{M}_{3\times 3}$ as $\mathbf{M}$. Equation (5) can be written as:

$$\mathbf{M} \begin{pmatrix} x_F \\ y_F \\ 1 \end{pmatrix} = \begin{bmatrix} \mathbf{R}_i^{\mathrm{T}}\mathbf{A}_i^{-1} & -\mathbf{R}_i^{\mathrm{T}}\mathbf{t}_i \end{bmatrix} \begin{pmatrix} \lambda u_i \\ \lambda v_i \\ \lambda \\ 1 \end{pmatrix}. \tag{8}$$

We can solve the linear equation (8) for the components of $\mathbf{M}$. This matrix depends upon the position, orientation and scale of the technical drawing. The matrix $\mathbf{M}$ describes a metric planar transformation, mapping an orthographic view onto a plane in the world coordinate system. Unlike the usual homography transformations between perspective images, this transformation is not homogeneous. Hence, all nine parameters of $\mathbf{M}$ need to be estimated. Each point correspondence provides two constraints, so we need a minimum of five point correspondences to estimate $\mathbf{M}$.

The left-hand side of (8) describes the mapping of points in the drawing to the world coordinate system. The right-hand side describes an optical ray in the world coordinate system. We also need to recover the direct mapping between the drawing and perspective images in order to blend them. Simple algebraic manipulation on (8) yields:

$$\mathbf{A}_i\mathbf{R}_i[\mathbf{m}_1 \quad \mathbf{m}_2 \quad \mathbf{m}_3 + \mathbf{R}_i^{\mathrm{T}}\mathbf{t}_i] \begin{pmatrix} x_F \\ y_F \\ 1 \end{pmatrix} = \lambda \begin{pmatrix} u_i \\ v_i \\ 1 \end{pmatrix}, \tag{9}$$

where $\mathbf{m}_k, k = 1, \ldots, 3$, are the column vectors of $\mathbf{M}$. This defines the direct mapping or homography between the technical drawing and each of the images as:

$$\mathbf{H}_i := \mathbf{A}_i\mathbf{R}_i[\mathbf{m}_1 \quad \mathbf{m}_2 \quad \mathbf{m}_3 + \mathbf{R}_i^{\mathrm{T}}\mathbf{t}_i], \tag{10}$$

and we have

$$\mathbf{H}_i \begin{pmatrix} x_F \\ y_F \\ 1 \end{pmatrix} = \lambda \begin{pmatrix} u_i \\ v_i \\ 1 \end{pmatrix}. \tag{11}$$

Therefore, once $\mathbf{M}$ has been estimated, homographies between the drawing and all calibrated images – often several hundreds – can be easily determined. In (10), each homography $\mathbf{H}_i$ is defined as a function of the intrinsic and extrinsic

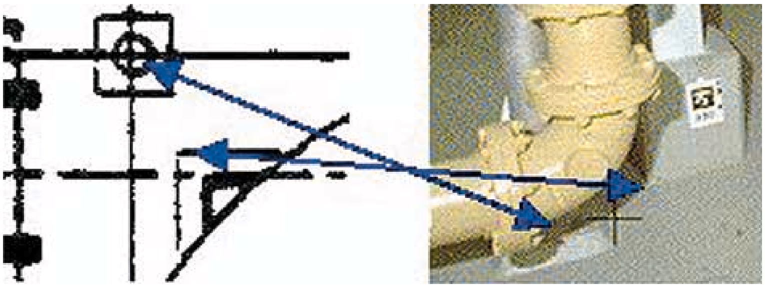


**Fig. 6.** Part of an image and the associated part of the floor map. The *arrows* indicate the correct correspondences. The corresponding points would ideally superimpose on each other

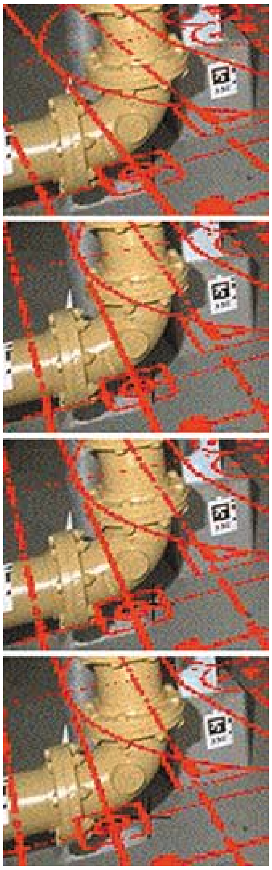



**Fig. 7a–d.** Superimposition of the floor map and an image from the database using different numbers of points for estimation of **M**. The technical drawings of the steel construction and the concrete foundation of a tank are superimposed onto real world images. In this experiment we use 5 (**a**), 8 (**b**), 11 (**c**), and 18 (**d**) point correspondences to estimate **M**

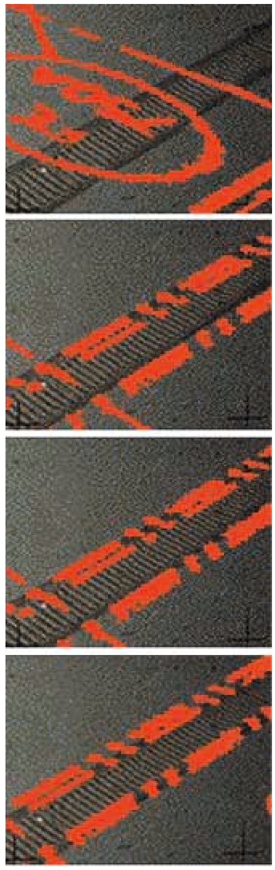



**Fig. 8a–d.** Superimposition of the floor map and an image from the database using different numbers of points for estimation of **M**. The technical drawing of a drainage channel is superimposed onto real world images. In this experiment we use 5 (**a**), 8 (**b**), 11 (**c**), and 18 (**d**) point correspondences to estimate **M**

parameters of each camera $(\mathbf{A}_i, \mathbf{R}_i, \mathbf{t}_i)$ and those of the drawing $\mathbf{M} = [\mathbf{m}_1 \quad \mathbf{m}_2 \quad \mathbf{m}_3]$. In many applications the intrinsic parameters remain constant ($\mathbf{A}_i = const.$). However, (10) also allows us to recover the homography $\mathbf{H}_i$ if the intrinsic parameters $\mathbf{A}_i$ change from one image to another.

Let us assume that we have obtained a homography $\mathbf{H}_i$ between the drawing and camera $i$ from (11) using a minimum of four point correspondences. $\mathbf{H}_i$ is defined up to a scale factor $\alpha_i$. Thus, it is not possible to uniquely extract $\mathbf{M}$. We have:

$$\mathbf{m}_1 = \alpha_i [\mathbf{R}_i^{\mathrm{T}} \mathbf{A}_i^{-1} \mathbf{H}_i]_1 \tag{12}$$

$$\mathbf{m}_2 = \alpha_i [\mathbf{R}_i^{\mathrm{T}} \mathbf{A}_i^{-1} \mathbf{H}_i]_2 \tag{13}$$

$$\mathbf{m}_3 = \alpha_i [\mathbf{R}_i^{\mathrm{T}} \mathbf{A}_i^{-1} \mathbf{H}_i]_3 - \mathbf{R}_i^{\mathrm{T}} \mathbf{t}_i, \tag{14}$$

where $[.]_k$ denotes the $k$'s column of a matrix. The factor $\alpha_i$ can only be determined if there is at least one additional point correspondence to a second image. Each pair of point correspondences between the drawing and an image provides two constraints. To recover the nine parameters of the matrix $\mathbf{M}$, we need to establish a minimum of five point correspondences between the drawing and two or more images. Note that one point correspondence between the drawing and two or more images only results in three independent equations for the following reason: A point can be reconstructed in 3D using two or more calibrated images. In theory, reconstruction from two or more images results in the same 3D point $\mathbf{x} = (x, y, z)^{\mathrm{T}}$. The 3D–3D correspondence between a 3D point reconstruction $\mathbf{x}$ and its representation in the drawing

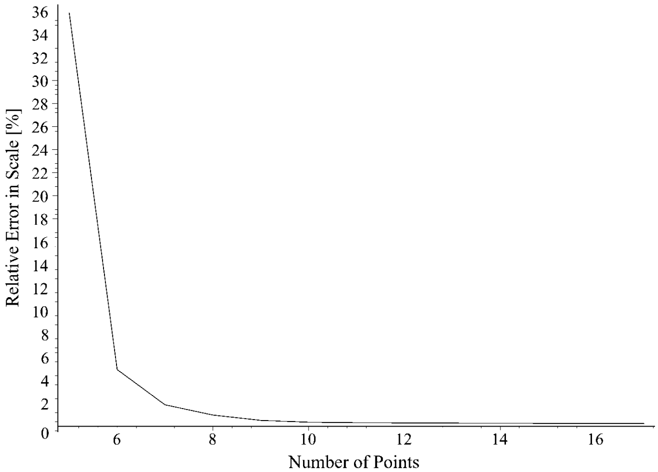



**Fig. 9.** Error in the estimated scale relative to the scale obtained using 18 point correspondences

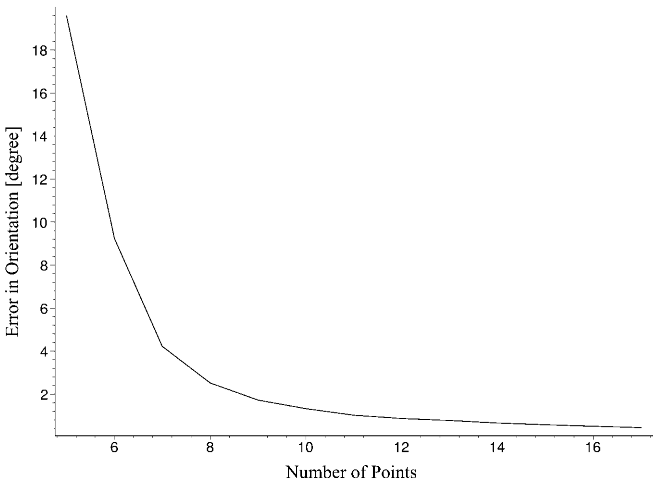



**Fig. 10.** Error in the estimation of orientation. The graph shows the absolute angle between the estimated rotation and rotation obtained using 18 point correspondences

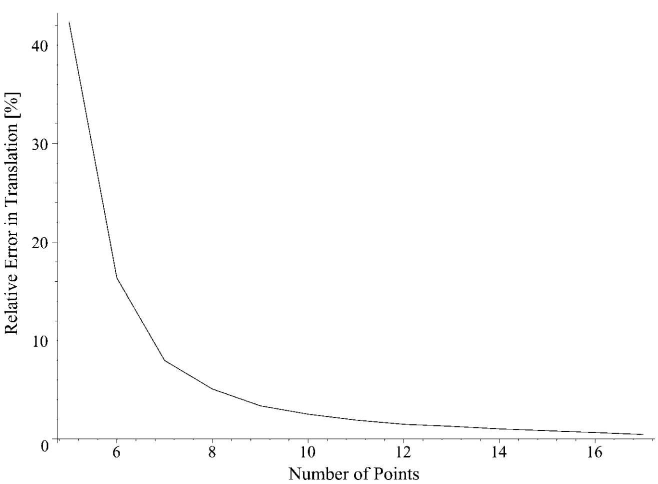



**Fig. 11.** Error in the estimated translation relative to the translation using 18 point correspondences. The graph shows the length of the difference vector

coordinate system $\mathbf{x}_F = (x_F, y_F, 0)^{\mathrm{T}}$ provides us with three equations: $\mathbf{M}\mathbf{x}_F + \mathbf{m}_3 = \mathbf{x}$ (see equation (8)). Therefore, one point correspondence between the drawing and two or more images theoretically results in only three independent equations. We thus need to use at least three different points in order to recover the nine parameters of **M**. This makes sense, since we need at least three distinct points to define a plane.

In summary, our algorithm consists of the following steps:

1. Establish at least five point correspondences between three or more distinct points on technical drawings and two or more images.
2. Estimate the metric planar transformation **M** using (8).
3. Compute homographies $\mathbf{H}_i$ between the drawing and all images in the database using (10).
4. Blend the drawing into the images using $\mathbf{H}_i$. If accuracy is sufficient, then stop.
5. Select additional point correspondences in the blended images[1].
6. Go to step 2.

## 6 Experiments on real data

To evaluate the accuracy and performance of our method on real data, we conduct two series of experiments. We apply our algorithm to a set of six calibrated images ($768 \times 512$ pixel), which are taken from a section of a waste water plant (see Fig. 2a). The associated floor map ($2800 \times 2244$ pixel) covers the whole building, i.e. much more than only the relatively small part covered by the images (see Fig. 2b).

We start by using five point correspondences between the floormap and two images. In the steps following we use 8, 11, 15 and, finally, 18 point correspondences in six images. The superimposition quality improves with the increasing number of correspondences. Figure 6 shows a part of an image and its associated parts in the technical drawing. Figures 7 and 8 show the results of superimposition.

The experiments show that, with a small number of point correspondences, the technical drawing can be registered to the image database with sufficient accuracy. This method can also be used to update the drawing. In this example, we use images of the main support structures to estimate **M**. The computation of matrix **M** and homographies $\mathbf{H}_i$ allows us to create an augmented reality representation of the factory. This new representation allows industry to access and manipulate industrial drawings and 3D models while interacting with their natural images. We call this new augmented reality representation a *transparent factory*.

The second set of experiments evaluates the influence of the number of point correspondences on the estimation of **M**. To study the error in scale, rotation and translation, we decompose the matrix **M**. We suppose that **M** is of the form

$$\mathbf{M} = [s_x\mathbf{r}_1 \quad s_y\mathbf{r}_2 \quad \mathbf{t}]. \tag{15}$$

The scale parameters $s_x$ and $s_y$ are approximated by the norm of the first and second columns of **M**. Furthermore, we estimate the floor map's orientation by

[1] Establishing correspondences between drawings and images is an easy task when the two documents are overlaid. This allows further automation.

$$\mathbf{R}_F = [\hat{\mathbf{m}}_1 \quad \hat{\mathbf{m}}_2 \quad \hat{\mathbf{m}}_1 \times \hat{\mathbf{m}}_2], \tag{16}$$

where $\hat{\mathbf{m}}_1$ and $\hat{\mathbf{m}}_2$ are the normalized column vectors of $\mathbf{M}$. Finally, the translation $\mathbf{t}_F$ is the last column vector of $\mathbf{M}$. This decomposition is not an exact one, and similar to decomposition of the projection matrix, it is quite noise sensitive. However, it allows us to present the numerical evaluation of the results. We establish 18 pairs of point correspondences between the floor map and images. We choose 500 random subsets of $N$, $N = 5 \ldots 15$, point correspondences from these 18 pairs. The number of possible subsets when using 16 and 17 pairs is less than 500. In these cases, all possible combinations are taken. Since we do not have a ground truth, we compare the results against those obtained using all 18 pairs of point correspondences. The graphs in Figs. 9, 10 and 11 show the smooth behavior of this algorithm. This confirms the results of the first set of experiments. The algorithm provides accurate results even if a small number of point correspondences is used.

## 7 Conclusion

In this paper, we propose a method to register and combine technical drawings, in particular floor maps, and a database of calibrated images. This method uses sparse pairs of point correspondences between a drawing and images in order to estimate the scale, orientation and position of the drawing in the world coordinate system. This results in simultaneous estimation of a set of homographies, which project the floor map onto all calibrated images. Experiments on a real application show that the method is successfully applied to create an augmented reality representation of a waste water plant. This method allows traditional industries to continue to use their favorite documents – technical drawings – while taking advantage of computer vision, 3D modelling and visualization technology.

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